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A New Ruthenium-Catalyzed Hydrogen-Transfer Reaction: Transformation of 3-Benzyl But-1-ynyl Ethers into 1,3-Dienes and Benzaldehyde

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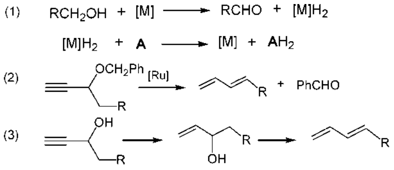
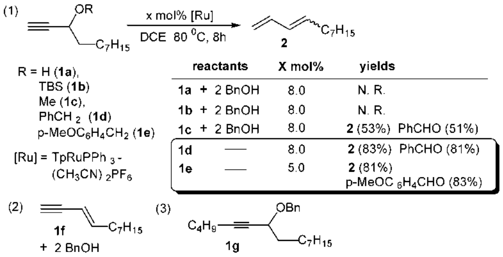
The metal-catalyzed hydrogen-transfer reaction between two organic substrates has attracted considerable attention because it is an energy-saving and environmentally friendly process.[1−4] This reaction avoids the use of conventional oxidants and reductants. Several hydrogen-transfer reactions have been shown to be useful in organic synthesis, and notable examples include the asymmetric hydrogenation of ketones and imines from formic acid or 2-propanol using chiral ruthenium[1a,2a,b] and aluminum catalysts.[3] Despite their synthetic importance, the scope of metal-catalyzed hydrogen-transfer reactions is rather limited. Many of them deal exclusively with the hydrogenation of a C═X (X = CR$_2$, NR, O) or C≡C bond by alcohols and formic acid.[1−4] An accepted mechanism of these catalytic reactions is shown in eq 1 (Scheme 1). We report here a new ruthenium-catalyzed reaction to effect the efficient conversion of various 3-benzyl but-1-ynyl ethers to 1,3-butadiene and benzaldehyde (eq 2). The direct synthesis of butadiene derivatives from but-1-yn-3-ol and its analogues is synthetically challenging and to the best of our knowledge has not yet been described. This transformation is normally achieved by stoichiometric LiAlH$_4$ reduction[5] or hydrogenation on Lindlar catalyst[6] to give allylic alcohols, followed by a tedious dehydration at elevated temperatures.[7] The mechanism (based on the results of the isotopic labeling experiment) of this new catalytic reaction appears to be interesting..

We first examined the catalytic transformation of various but-1-yn-3-ol derivatives **1a**−**1e** with TpRuPPh$_3$(CH$_3$CN)$_2$PF$_6$ catalyst to study the structural effect of the substrates. This catalyst was prepared directly by heating TpRu(PPh$_3$)$_2$Cl with LiPF$_6$ in CH$_3$CN.[8] The reaction was performed with ruthenium catalyst (8.0 mol %) in dichloroethane (80 °C, 12 h, [**1a**−**1e**] = 1.5 M), and the results are summarized in Scheme 2. No products were found for the alcohol **1a** and silyloxy derivative **1b** in the presence of benzyl alcohol (2.0 equiv) with exclusive recovery of unreacted **1a** and **1b**. A similar treatment on the methoxy **1c** gave the diene **2** (*E*/*Z* = 6.0, 53%) and benzaldehyde (51%), and 38% of unreacted **1c** was recovered. The yields of diene **2** (83%, *E*/*Z* = 6.0) and benzaldehyde (81%) were significantly improved when benzyl ether **1d** was used alone. *p*-Methoxybenzyl ether derivative **1e** is even more reactive and less catalyst (5 mol %) sufficed for the reaction. In the reaction involving enyne **1f** and benzyl alcohol (eq 2), a black tar and small amount of benzaldehyde (5%) were formed with complete consumption of enyne **1f**, showing a weak indication of transfer hydrogenation. The disubstituted alkynyl derivative **1g** was recovered in 92% under the same catalytic conditions.

Scheme 1

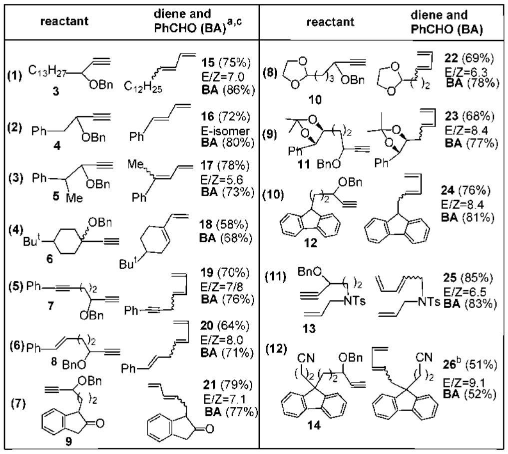


Scheme 2



reactants	X mol%	yields
1a + 2 BnOH	8.0	N. R.
1b + 2 BnOH	8.0	N. R.
1c + 2 BnOH	8.0	**2** (53%) PhCHO (51%)
1d —	8.0	**2** (83%) PhCHO (81%)
1e —	5.0	**2** (81%) p-MeOC$_6$H$_4$CHO (83%)

Table 1. Catalytic Transformation of 3-Benzyl But-1-y-nyl Ethers[a]



reactant	diene and PhCHO (BA)[a,c]	reactant	diene and PhCHO (BA)
(1) **3**	**15** (75%) E/Z=7.0 **BA** (86%)	(8) **10**	**22** (69%) E/Z=6.3 **BA** (78%)
(2) **4**	**16** (72%) E-isomer **BA** (80%)	(9) **11**	**23** (68%) E/Z=8.4 **BA** (77%)
(3) **5**	**17** (78%) E/Z=5.6 **BA** (73%)	(10) **12**	**24** (76%) E/Z=8.4 **BA** (81%)
(4) **6**	**18** (58%) **BA** (68%)	(11) **13**	**25** (85%) E/Z=6.5 **BA** (83%)
(5) **7**	**19** (70%) E/Z=7/8 **BA** (76%)	(12) **14**	**26**[b] (51%) E/Z=9.1 **BA** (52%)
(6) **8**	**20** (64%) E/Z=8.0 **BA** (71%)		
(7) **9**	**21** (79%) E/Z=7.1 **BA** (77%)		

[a] Conditions: (a) 8.0 mol % catalyst, 80 °C, 12 h (entries 1−11); (b) 15 mol % catalyst, 80 °C, 48 h; (c) the yields of diene and benzaldehyde were reported after separation on a silica column.

Table 1 shows various benzyl but-1-ynyl ethers that were catalyzed by TpRuPPh$_3$(CH$_3$CN)$_2$PF$_6$ catalyst. The reactions were performed with 8.0 mol % of the catalyst with heating in dichloroethane (1.5 M, 80 °C, 12 h) except for entry **12** which involved a higher loading of catalyst (15 mol %) for a longer time (80 °C, 48 h). The yields of diene products and benzaldehyde were calculated after purification from a silica column. Entries 1 and 2 shows two examples of the syntheses of dienes **15** and **16** bearing a C$_{13}$H$_{27}$ and phenyl group, respectively, in yields of 75 and 72%. This catalytic approach was also applicable to the efficient synthesis (78% yield) of trisubstituted diene **17** (entry 3) with an isomeric ratio of *E*/*Z* = 5.6. Similarly, the outer diene **18** (entry 4) was obtained in 58% yield. We prepared the substrates **7** and **8** bearing an alkene and alkyne group, respectively (entries 5 and 6). The corresponding dienes **19** and **20** were produced smoothly without hydrogenation of the saturated carbon−carbon bond by the benzyl group. This catalytic system also worked well for diene **21** bearing

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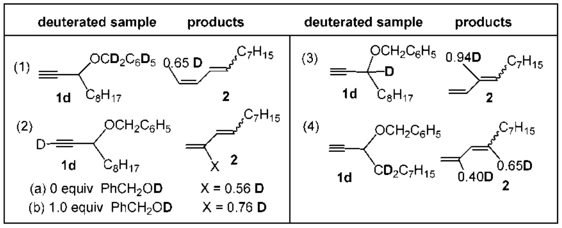
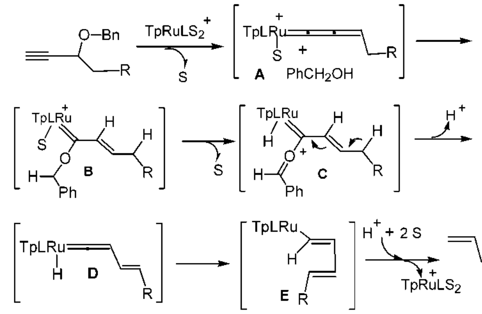
Scheme 3. Labeling Experiment for Hydrogen-Transfer Reaction



Scheme 4

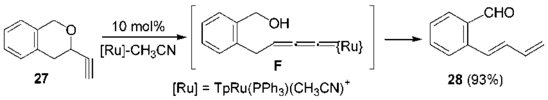


a ketone group. It also works well for dienes **22** and **23** comprising a dioxolane and a 2,2-dimethyloxolane group respectively; the yields were reasonable (68−69%, $Z/E = 6.3-8.4$). The acidic fluorenyl proton of compound **12** did not inhibit the catalytic reactivity, and the diene **24** (81%) was also produced smoothly. A nitrogen-containing diene **25** was obtained in 70% yield following this catalytic protocol. A higher loading of catalyst (15 mol %) was used to complete the reaction with compound **14** tethered to a nitrile group, and the yield of the corresponding diene **25** was 52% after workup.

Scheme 3 shows the results of deuterium-labeling experiments to elucidate the reaction mechanism. Deuterium migrations of ether **1d** to the diene **2** proceeded regiospecifically. The C_1-cis-proton of the diene arose primarily from the benzyl CH_2 protons of the diene **1d** (entry 1). The terminal acetylene proton of **1d** was transferred to the C_2-proton of the diene with 56% deuterium content (entry 2a). In the presence of one equimolar amount of $PhCH_2OD$, the deuterium content of this proton was increased to 76%. The site of the C_3-proton was unchanged after the reaction (entry 3). We also prepared **1d** bearing a deuterated C_4-methylene group, and a deuterium was found mainly at the C_4-diene and partly at the C_2-proton, whereas the remaining deuterium could not be found at one specific diene proton exclusively, including the C_1-trans position.[9]

On the basis of the results of deuterium experiments, we propose a plausible mechanism that involves the formation of ruthenium−allenylidenium **A**[10] which undergoes transformation into a more stable Fisher-carbenium **B**.[11,12] The benzyl group of **B** was activated by ruthenium after dissociation of its second CH_3CN, yielding species **C** bearing an oxonium group, which further induces ionization of its C_4-hydrogen to lead to the formation of ruthenium hydride species bearing an alkenyl vinylidenium species **D**. Hydride insertion at the C_1-carbon forms a 1,3-butadien-1-yl species. Decomplexation of this species with a proton and CH_3CN regenerates ruthenium catalyst and diene. This mechanism accounts for the results of deuterium-labeling experiment except for the result in entry 3. In this case, deuterium is expected to be located in the C_1-trans position of diene **2**. This discrepancy may be due to the proton exchange with diene[9] and benzene protons or residue water at reaction condition (80 °C, 12 h) (Scheme 4).

A useful application of this ruthenium catalyst is to transform the cyclic alkynyl ether **27** into the functionalized diene **28** (93% yield) under mild conditions (10 mol %, 80 °C, 12 h). The driving force for easy cleavage of the ether ring of **27** is the formation of ruthenium−allenylidene intermediate **F** which subsequently undergoes hydrogen transfer from its tethered alcohol to the allenylidene functionality.



27

28 (93%)

In summary, we report a new catalytic reaction involving a tandem dealkoxylation and transfer hydrogenation. The mechanism of this catalytic reaction was examined by deuterium experiments. This catalytic reaction is synthetically useful because it tolerates some oxygen and nitrogen functionalities. Further modification of the catalyst and the application of this reaction are under investigation.

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Supporting Information Available: Experimental procedures for the syntheses and spectral data of new compounds **1a**−**1e**,**2**−**28** (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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